WasteTwin: A Digital Twin of a Smart Waste Collection System-of-Systems

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1 Context and Industry Challenge

Municipal waste collection in dense urban areas is a complex problem, worsened by unpredictable weather, infrastructure limitations, and increasing citizen expectations. In Montréal, snowstorms and heavy rainfall often delay waste pickup, contributing to overflowing bins, public health risks, and loss of trust in city services[1]. Traditional systems lack the agility to adapt in real time or to anticipate disruptions, resulting in inefficiencies and elevated operational costs.

Contribution: *WasteTwin* addresses this challenge through the development of a Digital Twin (DT) tailored for a waste collection *System-of-Systems* (SoS). It demonstrates how data synchronization, environmental awareness, and bidirectional feedback loops can support urban service resilience. The SoS is composed of three autonomous but cooperating systems —smart waste bins, collection trucks, and traffic lights— each exhibiting both operational and managerial independence. Together, they form a decentralized infrastructure capable of adapting to environmental conditions and operational constraints.

2 Claim and Innovation

WasteTwin introduces the following key innovations:

- A fully functional closed-loop architecture combining real-time sensing, data ingestion, and actuation across physical and digital layers.
- Differentiation between passive Digital Shadows (trucks, traffic lights) and an active Digital Twin (smart bins), following SoS engineering principles.
- Integration of immersive 3D visualization using Godot, GDScript, and Blender, providing intuitive monitoring and feedback through a game-like interface.
- Multi-channel communication via MQTT (telemetry) and RabbitMQ (reliable command queuing), enhancing modularity and resilience.

This project is one of the few to bring together these features into a single prototype that can simulate, respond to, and influence a reference system in near real time. The resulting system highlights the self-organizing capacity of DT-enabled SoSs, particularly in situations involving unpredictable weather or urban congestion.

Hardware and Software Implementation

The reference system is realized using IoT components in the form of a mock-up and consists of three subsystems (CSs), each independently implemented using Raspberry Pis:

- **Traffic Lights (CS1):** Controlled via a Raspberry Pi using RGB LEDs to simulate stop-go sequences and simulating the urban traffic lights. Their states influence truck movement timing.
- **Collection Trucks (CS2):** Two servo-driven wheeled models simulate urban pickup. Brake actions are emulated via push buttons responding to traffic lights.

[1]CityNews: `https://montreal.citynews.ca/2025/02/20/montreal-garbage-snow-removal/`

- **Smart Bins (CS3):** Equipped with ultrasonic sensors, DHT modules, and LCD screens. The bins detect overflow, then report status to the DT for prioritization. The LCDs provide dynamic visual feedback.

The DT, hosted on a local Personal Computer (PC), subscribes to MQTT topics for live updates and sends task-oriented commands via RabbitMQ. It maintains fidelity through consistent synchronization between the mock-up's physical state and its 3D digital counterpart. The system's architecture is modular and expandable, allowing additional CSs or services (e.g., predictive analytics, scheduling optimization) to be incorporated.

The architecture is given in Figure 1

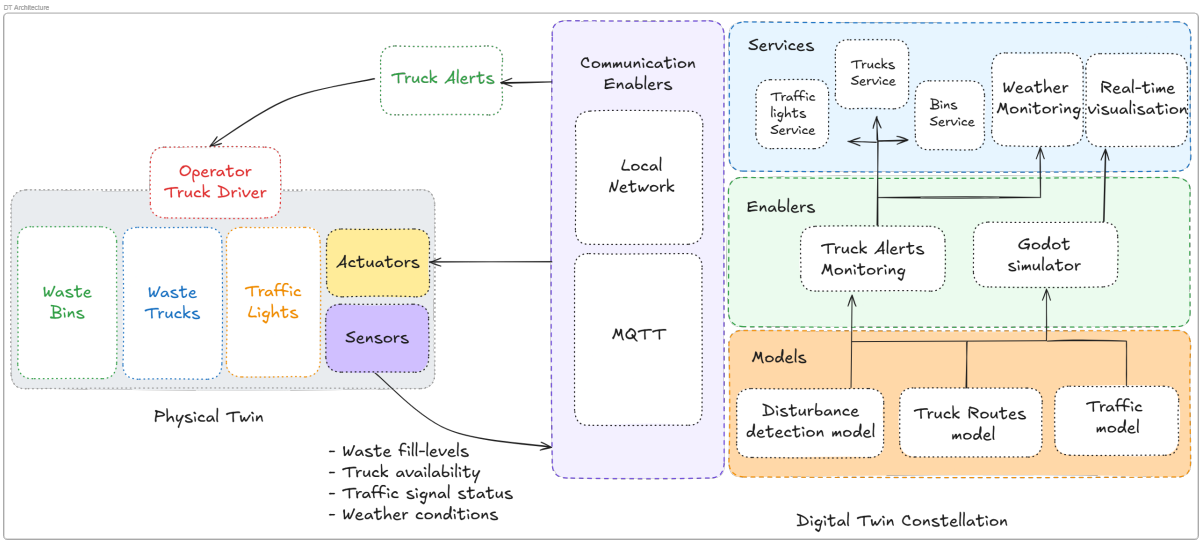

Figure 1: DT Architecture

Contribution to Knowledge and Practice

WasteTwin makes several academic and practical contributions:

- It provides a tangible implementation of a distributed, resilient DT-based SoS in the smart city domain, guided by architectural principles introduced by Smati et al. (2025).
- It validates the potential of real-time digital decision-making using local IoT feedback, especially in constrained environments like urban services.
- It proposes a methodological distinction between Digital Shadow and Digital Twin roles across different CSs, enabling researchers to stage their level of fidelity and responsiveness.
- It demonstrates the relevance of integrating gaming engines and open-source tools for rapid prototyping and realistic DT simulation.

This work sets the stage for more complex DT systems incorporating AI-based predictions, horizontal integration with other domains (e.g., water, energy), and standardized frameworks for system validation. The prototype also serves as an educational and demonstrative platform to bridge research and practice.

The full implementation is open-source[2] [3] and illustrates a novel way of tackling municipal resilience challenges through practical, modular digital twin design.

References

Smati, M., Cheutet, V., Danjou, C., & Laval, J. (2025). Digital twin system of systems: A layered architecture proposal. ScitePress.

[2]GitHub repository: `https://github.com/meriemsmt/wasteTwin`
[3]Demonstration video: `https://www.intranet.disp-lab.fr/s/y7aDjDamsB3LKgK`